ELEC412 Cheat Sheet

Chapter 3: PN Junctions

3.2 - Concept of PN Junction

Energy Band Diagram for a PN Junction

Built in potential: $\Phi_{bi} = kTln(\frac{N_A N_D}{n_i^2})$ **(1)**

I-V Characteristics of a PN Junction

$I = I_0 exp(V_a/V_t)$ **(2)**
Dynamic resistance: $R_{dyn} = \frac{d(V_a)}{dI} = \frac{V_t}{I}$ **(3)**
IV characteristics of pn junc. w/ rev. current:
$I = I_0 exp(V_a/V_t) - I_r$ **(4)**
If $I_r = I_0$ then $I = I_0[exp(V_a/V_t) - 1]$ - ideal diode eqn.**(5)**
Hole diffusion current flowing into the n-side in a p^+n junc.:
$I_p(x) = qD_p[d(p_n(x))/dx]A_{cs}$ **(6)**
$p_n(x) = p' exp(-x/L_p) + p_{n0}$ **(7)**
$d(p_n(x))/dx = -(p_n(x) - p_{n0})/L_p$ **(8)**
$I_p(x) = -qD_p(p_n(x) - p_{n0})A_{cs}/L_p$ **(9)**
$p' = p_{n0}[exp(qV_a/kT) - 1]$ **(10)**
$I_p = [qD_p n_i^2 A_{cs}/(N_D L_p)][exp(qV_a/kT) - 1]$ **(11)**
$I = I_p + I_n = I_0[exp(V_a/V_t)] - 1$ **(12)**
where $I_0 = qD_p n_i^2 A_{cs}/(N_D L_p) + qD_n n_i^2 A_{cs}/(N_A L_p)$
$I_G = qn_i W_j A_{cs}/(2\tau_0)$ **(13)**
$I = I_0 exp[(V_a/\eta_I V_t) - 1] - I_G$ **(14)**

Space-Charge and Charge Storage Effects

$C_{jun} = \varepsilon_s A_{cs}/W_j$ **(15)**
$W_j = \sqrt{2\varepsilon_s(V_{bi} - V_a)/(qN_{eff})}$ **(16)**
$W_j = [12\varepsilon_s(V_{bi} - V_a)/(qa)]^{1/3}$ **(17)**
$C_{diff} = [qA_{cs}(L_p p_{n0} + L_n p_{p0})/2V_t]exp(V_0/V_t)$ **(18)**
$C_{diff} \approx I_0\tau_p/(2V_t)$ **(19)**

Tunnel PN Junctions

$D_{12} = D_b exp(-2d_b\sqrt{2m_e^*(\Phi_B - E)}/h')$ **(20)**
$I_{tun} = qA_{cs}\int_{E_c}^{\acute{E}}[f_t S_1 D_{12} S_2]dE$ **(21)**

Junction Breakdown

$V_{br} = \epsilon_s \acute{E}_{cr}^2/(2qN_{eff})$ **(22)**
$d(j_n)/dx - (\alpha_i - \beta_i)j_n = -(\alpha_i - \beta_i)j_T + \alpha_i j_T$ **(23)**
If $\alpha_i = \beta_i$ then $M_n = j_n(L)/j_n(0) = 1/[1 - \int_0^L(\alpha_i)dx]$ **(24)**
$V_{br} \approx 4E_g/q$ **(25)**

Noise in PN Junctions

$\hat{i}^2 = 2q(I_d + 2I_0)\delta f$ **(26)**

Heterojunctions

$\Delta E_c = \xi_1 - \xi_2$ **(27)**
$\phi_{bi} = E_{g1} - \Delta E_n - \Delta E_p + \Delta E_c$ **(28)**
$W_j = W_n + W + p$ **(29)**
$W_n = \sqrt{2\epsilon_1\epsilon_2 N_A V_{bi}/[qN_D(\epsilon_2 N_D + \epsilon_1 N_A)]}$
$W_p = \sqrt{2\epsilon_1\epsilon_2 N_D V_{bi}/[qN_A(\epsilon_2 N_D + \epsilon_1 N_A)]}$
$C_{jun} = \sqrt{\epsilon_1\epsilon_2 N_D N_A/[2(\epsilon_2 N_D + \epsilon_1 N_A)V_{bi}]}$ **(30)**
$I = I_0(1 - V_a/V_{bi})[exp(V_a/V_t) - 1]$ **(31)**

3.3 - Schottky Junction

Schottky Junction at Equilibrium

$f_{vx} = \sqrt{[m_e^*/(2\pi\Phi_t)]exp[-m_e^* v_x^2/(2\Phi_t)]}$ **(32)**
$\Phi_t = kT$
$\langle v_x\rangle = \int_0^\infty[v_x f_{vx}]dv_x = \sqrt{\Phi_t/(2\pi m_e^*)}$ **(33)**
$I = -qA_{cs}\int_0^\infty[v_x \partial n/\partial E]dE$ **(34)**
$I_{sm} = A^*T^2 A_{cs} exp[(-\Phi_{bi} - E_n)/\Phi_t]$ **(35)**
$I_{ms} = -A^*T^2 A_{cs} exp[-\Phi_B/\Phi_t]$ **(36)**
At equilib., no net current flowing $I_{sm} = -I_{ms}$
give $\Phi_B = \Phi_{bi} + E_n$ **(37)**

Schottky Junction under Bias

$\Phi_{bi} = \Phi_B - E_n - qV_a$ **(38)**
Total fwd-bias current $I = I_{sm} + I_{ms}$ **(39)**
$= A^*T^2 A_{cs} exp(-\Phi_B/\Phi_t)[exp(V_a/V_t) - 1]$
$= I_0[exp(V_a/V_t) - 1]$
where $I_0 (= A^*T^2 A_{cs} exp(-\Phi_B/\Phi_t))$ is the saturation current
$I_{tun} = I_f exp(\Phi_B/E_\infty)$ **(40)**
$E_\infty = qh/4\pi\sqrt{N_D/(\epsilon_s m_e^*)}$

Nonideal Schottky Junctions

Schottky barrier height $\Phi_B = E_g - \Phi_0$ **(41)**
$\Delta\Phi_B = q\sqrt{qE'/(4\pi\epsilon_s)}$ **(42)**
$I_p = (qD_p p_{n0} A_{cs}/L_p)[exp(V_a/V_t - 1)]$ **(43)**
$\gamma^* = I_p/I$ **(44)**
$I = A^*T^2 A_{cs} exp(-\Phi_B/\Phi_t)[exp(V_a/(\eta_I V_t)) - 1]$ **(45)**

Capacitance Effect and Equivalent-Circuit Model of a Schottky Junction

$C_{jun} = A_{cs}\sqrt{qN_D\epsilon_s}$ **(46)**

Modification of the Barrier Height

$\Phi_B^* = \Phi_B - q/\epsilon_s\sqrt{n_1 a'/4\pi}$ **(47)**
$\Delta d = [a' p_1 - (W - a')n_2]/p_1$ **(48)**
$\Phi_B^* = \Phi_B + q^2 p_1\Delta d^2/2\epsilon_s$ **(49)**

3.4 - Metal-Semiconductor Contact

$R_c = \sqrt{R_{sh} r_c}/d_c coth[L\sqrt{R_{sh}/r_c}]$ **(50)**
$R_{sh} = r_{sheet} L_{sh}/d_c$ **(51)**
$R = R_c + R_{sh} + R_{sp}$ **(52)**
$r_c \approx exp[2V_{bn}\sqrt{\epsilon_s m_e^*/N_D}/(h')]$ **(53)**

3.5 - MIS Junction and Field-Effect Properties

$V_{FB} = [\Phi_m - \Phi_s - (E_c - E_f)]/q$ **(54)**

Surface Inversion

$V_m = V_s + \sqrt{2\epsilon_s qN_A V_s}/C_i$ **(55)**
$n_s = n_{p0} exp(V_s/V_t)$ **(56)**
$p_s = p_{p0} exp(-V_s/V_t)$
$V_t = kT/q$
$\acute{E}_s = \sqrt{2}(V_t/L_{D_p})\cdots$ **(57)**
$\cdot\sqrt{[exp(-V_s/V_t) + V_s/V_t - 1]n_{p0}/p_{p0}[exp(V_s/V_t) - V_s/V_t - 1]}$
$V_a = 2\phi_b - \sqrt{4qN_A\phi_b\epsilon_s}/C_i$ **(58)**
$V_T^* = V_T + V_{FB} + V_{sc} + V_{sub}$ **(59)**

Capacitance Effect in a MIS Junction

$C_{mis} = C_i C_{depl}/(C_i + C_{depl})$ **(60)**

3.7 - Structure and Operations of Transistors

Field-Effect Transistors (FETs)

$Q_s = -C_i[V_g - 2\phi_b - V_{FB} - V_c(x)]$ **(61)**
$n_{ss}(x) = Q_s - \sqrt{2\epsilon_s qN_A(V_c(x) + 2\phi_b)}$ **(62)**
$I_{ds} = qn_{ss}W_c\mu_n dV_c(x)/dx$ **(63)**
$I_{ds} = (\mu_n W_c/L)C_i\{(V_g - V_{FB} - 2\phi_b - V_{ds}/2) - (2/3)\cdots$ **(64)**
$\cdot[\sqrt{2\epsilon_s qN_A}/C_i][(V_{ds} + 2\phi_b)^{3/2} - (2\phi_b)^{3/2}]\}$
$V_{ds} = V_g - V_T$ **(65)**
$V_T = V_{FB} + 2\phi_b + V_{sc} + \sqrt{2\epsilon_s qN_A(2\phi_b - V_{sub})}/C_i$ **(66)**
$I_{ds} \approx \beta_0(V_g - V_T)V_{ds}$ **(67)**
$\beta_0 = \mu_n C_i W_c/L$
$I_{D_{sat}} \approx \beta_0(V_g - V_T)^2/2$ **(68)**
$g_m = \beta_0(V_g - V_T)$ **(69)**
$I_{ds} = I_{D_{sat}} tanh(g_{ds}V_{ds}/I_{D_{sat}})[1 + \gamma' V_{ds}]$ **(70)**
$\Delta I_{ds} = g_m\Delta V_g = \beta_0(V_g - V_T)\Delta V_g$ **(71)**
$G_v = \beta_0(V_g - V_T)R_L$ **(72)**
$\Delta V = I_{ds}\Delta x/[q\mu_n N_D W_c(t_c - a_d(x))]$ **(73)**
$a_d(x) = 2\epsilon_s(V(x) + V_{bi} - V_g)/(qN_D)$
$I_{ds} = g_0[V_{ds} - 2((V_{ds} + V_{bi} - V_g)^{3/2} - (V_{bi} - V_g)^{3/2})/(3\sqrt{V_{po}})]$ **(74)**
$g_m = g_0(\sqrt{V_{ds} + V_{bi} - V_g} - \sqrt{V_{bi} - V_g}/\sqrt{V_{po}})$ **(75)**
$V_{D_{sat}} = V_{po} - V_{bi} + V_g$
$I_{D_{sat}} = g_0(V_{po}/3 + 2(V_{bi} - V_g)^{3/2}/(3\sqrt{V_{po}}) - V_{bi} + V_g)$ **(76)**
$g_m = g_0[1 - \sqrt{(V_{bi} - V_g)/V_{po}}]$
$I_{ds} = \beta'(V_g - V_T)^2(1 + \gamma' V_{ds})tanh(g_0 V_{ds}/I_{D_{sat}})/[1 + b(V_g - V_T)]$ **(77)**
$\beta' = \mu_n\epsilon_s W/(t_c L)$
$V_T = V_{bi} - V_{po}$
$I_{gate} = I_{gs} + I_{gd}$ **(78)**
$I_{gs} = I_{go} exp\{[V_{gs} - I_g R_g - (I_{ds} + I_{gs})R_s](\eta_g V_{th})\}$
$I_{gd} = I_{go} exp\{[V_{gd} - I_g R_g - (I_{ds} + I_{gd})R_s](\eta_g V_{th})\}$

Bipolar Junction Transistor (BJT)

$D_{pb}d^2(p_b(x) - p_{n0})/dx^2 - (p_b(x) - p_{n0})/\tau_p = 0$ **(79)**
$p_b(x) = p_{n0} + A_{b1} exp(x/L_{pb}) + A_{b2} exp(-x/L_{pb})$ **(80)**
$p_b(x) = p_{n0}[exp(V_a/V_t - 1)]sinh[(W' - x/L_{pb})]/sinh[W'/L_{pb}]$ **(81)**
$\cdots + p_{n0}[1 - sinh(x/L_{pb})/sinh(W'/L_{pb})]$
$p_b(x) \approx p_{n0}[exp(V_a/V_t - 1)][1 - x/W']$ **(82)**
$I_{pb} = -qD_{pb}d(p_b(x))/dx A_{cs} = qD_{pb}p_{n0}[exp(V_a/V_t - 1)]A_{cs}/W'$ **(83)**
$n_e(x) = n_{p0} + n_{p0}[exp(V_a/V_t) - 1]exp[(x + x_e)/L_{ne}]$ **(84)**
$n_c(x) = n_{p0} + n_{p0}[exp(-(x - x_c)/L_{nc})]$
$I_{ne} = qD_{ne}n_{p0}A_{cs}[exp(V_a/V_t - 1)]/L_{ne}$ **(85)**
$I_{nc} = qD_{nc}n_{p0}A_{cs}/L_{nc}$
During device operation: $I_e \approx I_{ne}$
$I_c = I_{nc}$ **(86)**
$I_b = I_{pb}$
$\beta_g \approx D_{pb}N_{Ae}x_e/(D_{ne}N_{Db}W')$ **(87)**
$Q_G = \int_0^{W'}[N_{Db}(x)]dx \approx W' N_{Db}$ **(88)**
$n_b(0) = p_b(0) \approx n_i exp(V_a/2V_t)$ **(89)**
$I_e \approx I_c \approx (qn_i D_{pb}A_{cs}/W')exp(V_a/2V_t)$ **(90)**
$I_b \approx qD_{ne}n_i^2 A_{cs}/(x_e N_{Ae})exp(V_a/V_t)$

3.8 - Nonideal Effects and Other Performance Parameters

MOSFETs

$\mu^* = \mu_0/(1+\mu_0\acute{E}/v_s)$ **(91)**
$I_{ds} = qn_{ss}v_n(\acute{E})W_c$ **(92)**
$V_c(x) = V_{gt} - \sqrt{V_{gt}^2 - 2I_{ds}x/\beta_0 L}$ **(93)**
$V_{gt} = V_g - V_T$
$\beta_0 = \mu^* C_i W_c/L$
$I_{D_{sat}} = \beta_{sl}V_{sl}^2[\sqrt{(1+(V_{gt}/V_{sl}))^2} - \beta_{sl}V_{sl}^2]$ **(94)**
$V_{sl} = \acute{E}_p L$
$I_{sub} = -qA_{cs}D_n\Delta n/\Delta x$ **(95)**
$= \epsilon_s\mu_n(W_c/L)V_t^2(n_i/N_A)^2\sqrt{V_t/V_s}exp(V_s/V_t)\cdots$
$\cdot[1-exp(-V_{ds}/V_t)]/(\sqrt{2}L_{Dp})$
In saturation, these capacitances are given by:
$C_{gs} = C_{gsf} + 2C_iW_cL/3$
$C_{gd} = C_{gdf}$
$C_{gb} = 0$
$C_{bs} = C_{js}(1+\frac{2}{3}C_{gb}/C_{js}W_cL)/(1+V_{sub-s}/\phi_{bi})^{mB}$
$C_{bd} = C_{jd}/(1+V_{sub-d}/\phi_{bi})^{mB}$ **(96)**
In the linear regime, the same parameters are given by:
$C_{gs} = C_{gsf} + \frac{2}{3}C_iW_cLV_{D_{sat}}(3V_{D_{sat}} - 2V_{ds})/(2V_{D_{sat}} - V_{ds})^2$
$C_{gs} = C_{gdf} + \frac{2}{3}C_iW_cL(V_{D_{sat}} - V_{ds})(3V_{D_{sat}} - V_{ds})\cdots$
$/(2V_{D_{sat}} - V_{ds})^2$
$C_{gb} = 0$ **(97)**
$C_{bs} = C_{js}[1+\frac{2}{3}C_{gb}/C_{js}W_cLV_{D_{sat}}(3V_{D_{sat}} - 2V_{ds})\cdots$
$/(2V_{D_{sat}} - V_{ds})^2]/(1+V_{sub-s}/\phi_{bi})^{mB}$
$C_{bd} = C_{jd}[1+\frac{2}{3}C_{gb}/C_{js}W_cL(V_{D_{sat}} - V_{ds})(3V_{D_{sat}} - V_{ds})\cdots$
$/(2V_{D_{sat}} - V_{ds})^2]/(1+V_{sub-s}/\phi_{bi})^{mB}$
$f_T = g_m/[2\pi(C_g + C_p)]$ **(98)**
$\Delta V_{TE} = \Delta V_{bi} + q\Delta n_A/C_i$ **(99)**
$\Delta V_{TD} = \Delta V_{bi} - \Phi_x/q - q\Delta n_D/C_i$
$\hat{i}_{th}^2 = 4kTg_{do}$ **(100)**
$C' = C_i/k^*$
$I'_{D_{sat}} = I_{D_{sat}}/k^*$ **(101)**
$f'_T = k^* f_t$
$P'_{ac} = P_{ac}/(k^*)^2$

MESFETs

$I_{D_{sat}} = \beta''(V_G - V_T)^2$ **(102)**
$\beta'' = 2\epsilon_s\mu_n v_s W_c/[t_c(\mu_n V_{po} + 3v_sL)]]$
$V_T = V_{bi} - V_{po}$
$C_{gs} = C_{go}/\sqrt{1 - V_{gs}/V_{bi}} + \pi\epsilon_s W_c/2$ **(103)**
$C_{gd} = C_{go}/\sqrt{1 - V_{gd}/V_{bi}} + \pi\epsilon_s W_c/2$
$L/t_c < 3$ and $N_D L \approx 1.6 \text{ x } 10^{23}\mu m/m^3$ **(104)**

BJTs

$\Delta E_g = 3q^2\sqrt{qN_{De}/\epsilon_s \cdot V_t}/16\pi\epsilon_s$ **(105)**
$N_{Ab} \approx N_{Ao}exp[-(x-x_e)/\lambda_b]$ **(106)**
$\beta^* \approx \beta_g W'/2\lambda_b$ **(107)**
$\Delta Q_{bs} = (I_{b1} - I_{b2})\tau_{sr}exp(-t/\tau_{sr}) + (I_{b2} - I_{ba})\tau_{sr}$ **(108)**
$\tau_s = \tau_{sr}ln[(I_{b1} - I_{b2})/(I_{ba} - I_{b2})]$ **(109)**
$f_\beta = (C_e r_e)/2\pi$ **(110)**
$f_\beta = g_{b'e}/2\pi(C_{b'e} + C_{b'c})$ **(111)**
$f_{tr} = < v > /W'$ **(112)**
$BV_{cb} = \epsilon_s\acute{E}_{cr}^2/(2qN_{Dc})$ **(113)**
$BV_{ce} = BV_{cb}(1-\alpha_g)^{1/mb}$ **(114)**
$V_{pt} = qN_{Ab}W'^2/(2\epsilon_s N_{Dc})$ **(115)**
$\hat{i}_1^2 = 2q(I_e + 2I_b)\partial f$ **(116)**
$\hat{i}_2^2 = 2qI_c\partial f$

3.9 - New Transistor Structures

Heterojunction Bipolar Transistor (HBT)

$\beta_{max} = v_{nb}N_{De}x_e/(v_{pe}N_{Ab}W')exp(\Delta E_v/(qV_t))$ **(117)**
$\tau_d = 2.5R_BC_{b'c} + R_B\tau_B/R_L + (3C_{b'c} + C_L)R_L$ **(118)**
$f_T = 1/[2\pi\tau_{tr}(1 + C_L/C_g)]$ **(119)**
$V_T = \frac{(\Phi_B - \Delta E_c)}{q} - qN_Dd_{dd}^2/(2\epsilon_1)$ **(120)**
$V_T = \frac{(\Phi_B - \Delta E_c)}{q} - \frac{qn_sd_d}{\epsilon_1}$ **(121)**
$I_{ds} = q\mu_n n_{xs}d(V_a)/dx$ **(122)**
$n_{xs} = n_s - \epsilon_1 V_a(x)/(qd_{eff})$
$I_{ds} = \mu\epsilon_1(W_c/L)[(V_g - V_T)V_{ds}/d_{eff} - V_{ds}^2/(2d_{eff})]$ **(123)**
$V_{D_{sat}} = (qn_s/\epsilon_1)(1 + a' - \sqrt{1 + a'^2})$ **(124)**
$I_{D_{sat}} = qn_s\mu_n\acute{E}_sW_c(\sqrt{1+a'^2} - a')$
$\acute{E}_s = v_s/\mu_n$
$a' = \epsilon_1 v_s L/(qn_s\mu_n d_{eff})$

Amorphous Silicon Thin-Film Transistor (TFT)

$Q_D = qg_{vd}E_{donor}exp[(E_v - E_F)/E_{donor}]$ **(125)**
$Q_A = qg_{cd}E_{acceptor}exp[(E_F - E_c)/E_{acceptor}]$
$E_c - E_{F0} = E_{acceptor}/(E_{acceptor} - E_{donor})\cdots$ **(126)**
$\cdot[E_g - E_{donor}ln(g_{vd}E_{donor})/(g_{cd}E_{acceptor})]$
$I_{ds} = q\mu n_s d(V_a)/dxW_c$ **(127)**
$n_{ind} = n_{inds} - \epsilon_i V_a/(qd_i)$ **(128)**
$I_{ds} = q\mu^{**}W_c/Ln_{inds}V_{ds}$ **(129)**
$V_{D_{sat}} = qn_{inds}d_i/\epsilon_i$ **(130)**

Glossary of Variables

Φ_{bi} is the build-in potential
$V_{bi}(=\Phi_{bi}/q)$ is the build-in voltage in V
k(8.62 x $10^{-5}ev/K$): Boltzmann constant
T: absolute temp. in Kelvin
n_i is the intrinsic carrier density of the semiconductor $/m^3$
N_A is the acceptor density $/m^3$
N_D is the donor density $/m^3$
V_a is the applied voltage and is a fixed voltage in V
I_0 is the saturation current in A
$V_t(=kT/q)$ is the thermal voltage (0.026V unless said otherwise)
R_{dyn} is the dynamic resistance (Ω)
I_r is the reverse current (or leakage current)
I_p is the hole diffusion current flowing into the n side in a p^+n
q (1.602 x 10^{-19} C) is the electron charge in C
D_p is the hole diffusivity in m^2/s
D_n is the electron diffusivity in m^2/s
A_{cs} is the cross section of the pn junc in m^2
$d(p_n(x))/dx$ is the hole density grad. in the n-side in $/m^4$
p' is the excess hole density at x=0 in $/m^3$
$p_{n0}(=n_i^2/N_D)$ is the equilib. hole density in the n-side in $/m^3$
$p_{p0}(=n_i^2/N_A)$
L_p is the diffusion length of the holes in m
L_n is the diffusion length of the electrons in m
I_G thermal generation current
τ_0 is the generation lifetime of the carriers in s
τ_p is the lifetime of the holes in s
W_j is the width of the junc. region in m
η_I is the ideality factor, takes into account the recomb. effect
ε_s is the semiconductor permittivity in F/m
C_{jun} is the junction capacitance in F
$N_{eff} = N_AN_D/(N_A + N_D)$
a is the gradient of the dopant density in $/m^4$
V_0 is the forward-bias voltage in V
D_{12} the transmission coefficient (prob. that tunnelling event will occur)
D_b is a constant
m_e^* is the effective mass of the electrons in kg
d_b is the barrier width in m
$h'(=1.05 \text{ x } 10^{-34}J\cdot s)$ is Planck's constant divided by 2π
I_{tun} is the tunneling current in A
$S_1 and S_2$ are the respective densities of states of E. bands in the two sides of the PN junction in $/m^3$
f_t is a tunneling freq. parameter in $m^4/s\cdot eV$
E_c is the E. at the conduction band edge in eV
$\acute{E}$ is the upper E. limit for tunneling in eV
$\acute{E}_{cr}^2$ is the critical field
V_{br} is the breakdown voltage in V
j_n is the electron current density in A/m^2
j_p is the hole current density in A/m^2
$j_T(=j_n + j_p)$ is the total current density in A/m^2
α_i is the electron ionization rate in /m
β_i is the hole ionization rate in /m
L is the length of the ionization region in m
M_n is the electron multiplication factor
E_g is the E. gap of the semiconductor in eV
$\hat{i}^2$ is the shot noise (generated when carriers cross a barrier) in A^2
I_d is the diode current in A
I_0 is the saturation current in A

δf is the freq. range in Hz
ξ_1 and ξ_2 are the respective electron affinities in the two semiconductors
E_{g1} is the E. gap of the narrow-gap p-type semiconductor in eV
ΔE_n is the E. difference between the conduction band edge and the Fermi level in the wide-gap semiconductor in eV
ΔE_p is the E. difference between the valence band edge and the Fermi level in the narrow-gap semiconductor in eV
ϵ_1 and ϵ_2 are the respective permittivities of the p-type and n-type semiconductors in F/m
v_x is the velocity of the electrons in the +x direction in m/s
m_e^* is the effective mass of the electrons in kg
$\langle v_x \rangle$ is the average velocity of electrons in m/s
f_{vx} is the velocity distribution of the electrons
$\partial n/\partial E$ is the rate at which the electron density changes with E. band in $/m^3 \cdot eV$
I_{sm} is the current of electrons moving from the semiconductor into the metal (pos. value)
$A^*(= 4\pi q m_e^* k^2/h^3 = 1.2$ x $10^6 A/m^2 \cdot K^2$ is called the Richardson constant
E_n is the E. diff. between the semiconductor Fermi lvl and the conduction band edge in eV
Φ_B is the barrier height in eV
E_∞ is a parameter dependent on the dopant density in J
I_f is a pre-exponential constant that depends on the field-emission process in A
Φ_0 is the location of the surface Fermi level in eV
E' is the electric field in V/m
$\Delta\Phi_B$ is the resulting lowering in the barrier height in eV - usually quite small ($\approx 0.01eV$)
I_p is the minority carrier current in A
γ^* is the minority carrier injection ratio
I is the total current flowing across the Schottky junction in A
a' is the dopant layer thickness in m
n_1 is the interface dopant density in $/m^3$
n_2 is the substrate donor density in $/m^3$
W is the depletion-layer width in m
Δd is the distance away from the interface in m
Φ_B^* is the effective barrier height in m
p_1 is the surface dopant density in $/m^3$
p_2 is the surface dopant density in $/m^3$
R_c is the contact resistance in Ω
R_{sh} is the shunt resistance in Ω
r_c is the specific contact resistance in $\Omega \cdot m^2$
d_c is the width of the contact in m
L is the contact length in m
r_{sheet} is the semiconductor sheet resistance in Ω/square
L_{sh} is the length of the shunt path in m
m_e^* is the effective mass of the electrons in kg
$V_{bn}(= \Phi_B/q)$ is in V
h' is Planck's constant divided by 2π
N_D is the donor density in $/m^3$
V_{FB} is the flat-band voltage in V (can be pos. and neg.)
Φ_m is the metal work function in eV
Φ_s is the semiconductor work function in eV
$E_c - E_F$ is the E. diff. between the conduction band edge and the Fermi lvl in the semiconductor in eV
V_s is the potential at the semiconductor surface in V
C_i is the oxide capacitance per unit are in F/m^2
n_{p0} is the equilib. electron density in the p-type semiconductor in $/m^3$
p_{p0} is the equilib. hole density in the p-type semiconductor in $/m^3$
p_s is the surface charge density for the electrons in $/m^3$
n_s is the surface charge density for the holes in $/m^3$
$\acute{E}_s$ is the electric field at the semiconductor's surface in V/m
L_{D_p} is the hole-diffusion length in m
V_T is the threshold voltage in V
V_T^* is the modified threshold voltage in V
V_{sc} is the potential drop due to oxide charges in the insulator in V
V_{FB} is the flat-band voltage in V
V_{sub} is the substrate bias voltage in V
C_{mis} is the MIS junction capacitance in F/m^2
C_i is the insulator capacitance per unit area in F/m^2
C_{depl} is the depletion layer in capacitance per unit area in F/m^2
Q_s is the surface charge density in C/m^2
V_g is the gate voltage in V
$2\phi_b$ is the change in the surface potential in V required to generate strong inversion
$V_c(x)$ in V is the channel potential, which varies along the length of the channel in the x direction
$n_{ss}(x)$ is the effective electron density along the channel in $/m^2$
μ_n is the channel mobility in $m^2/V \cdot s$
$dV_c(x)/dx$ is the incremental change in the channel potential divided by the incremental change in position in V/m
W_c is the channel width in m
V_{ds} is the drain-to-source voltage in V
L is the channel length in m $V_g - V_{ds}$ is the voltage drop across the drain-substrate PN junction in V
V_T is the threshold voltage in V
g_m is the transconductance of the MOSFET in $/\Omega or S$
γ' is an empirical parameter in /V
$I_{D_{sat}}$ is the saturation current in A
I_{ds} is the drain-source current in A
$G_v(= \Delta I_{ds} R_L/\Delta V_g)$ is the voltage gain
R_L is the resistive load in Ω
Δx is the incremental channel length in m
W_c is the width of the MESFET in m
t_c is the thickness of the active layer in m
g_0 is the channel conductance in $\Omega or S$
$V_{po}(= qN_D t_c^2/(2\epsilon_s))$ is the pinch-off voltage in V
γ' and b are empirical constants in /V
I_{go} is the gate saturation current in A
R_g is the gate resistance in Ω
η_g is the ideality factor for the gate junction
D_{pb} is the hole diffusivity in the base in m^2/s
p_{n0} is the equilibrium hole density in the base in $/m^3$
τ_p is the hole lifetime in s
A_{b1} and A_{b2} are constants in $/m^3$
$L_{pb}(= \sqrt{D_{pb}/\tau_p}$ is the hole diffusion length in the base in m
L_{ne} and L_{nc} in m are the electron diffusion lengths in the emitter and collector
x_e and x_c in m are the widths of the base-emitter junc. and base-collector junc.
I_{ne} and I_{nc} in A are the electron-diffusion currents in the emitter and collector
D_{ne} and D_{nc} in m^2/s are the diffusivities of the electrons in the emitter and collector
L_{ne} and L_{nc} in m are the diffusion lengths of the electrons in the emitter and collector
N_{Ae} is the acceptor density in the emitter in $/m^3$
N_{Db} is the donor density in the base in $/m^3$
Q_G is the Gummel number in base doping per unit area
$\beta_g(= \Delta I_c/\Delta I_b)$ is the common-emitter current gain